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Fluvial organic carbon flux from an eroding peatland catchment, southern Pennines, UK

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HESSD

4, 719–745, 2007

**Fluvial organic
carbon flux from an
eroding peatland**

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

Abstract

This study investigates for the first time the relative importance of dissolved organic carbon (DOC) and particulate organic carbon (POC) in the fluvial carbon flux from an actively eroding peatland catchment in the southern Pennines, UK. Event scale variability in DOC and POC was examined and the annual flux of fluvial organic carbon was estimated for the catchment. At the event scale, both DOC and POC were found to increase with discharge, with event based POC export accounting for 95% of flux in only 8% of the time. On an annual cycle, 40.8 t organic carbon (OC) is exported from the catchment, which represents an areal value of 107 gC m⁻² a⁻¹. POC was the most significant form of organic carbon export, accounting for ~82% of the estimated flux. This suggests that more research is required on both the fate of POC and the rates of POC export in eroding peatland catchments.

1 Introduction

There is a wide range of literature investigating the fluvial export of organic carbon from peatland environments (e.g. Dawson et al., 2002; Worrall et al., 2003 and Hope et al., 1997a). Much of this research has been focussed upon estimating total fluvial losses of organic carbon in the form of DOC (dissolved organic carbon) and POC (particulate organic carbon), especially in light of current and potential climatic changes and the likely impacts of such changes on the soil carbon store. Understanding POC and DOC losses and their impact on upland carbon budgets is essential in light of potential future climate changes and targets for carbon sequestration set by the Kyoto Protocol. In the UK the largest component of soil carbon storage is present in upland peat soils (Worrall et al., 2003; Wallage et al., 2006). Integrated studies of riverine export have shown an important link between terrestrial and oceanic carbon storage (Hope et al., 1997b and Kempe, 1979). In most studies that have evaluated the total losses of DOC and POC through upland fluvial systems, DOC is identified as the most

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

significant form of carbon export. For example, Hope et al. (1997a) assessed two contrasting rivers in NE Scotland. Of these, DOC export accounted for greater than 75% of the total fluvial loss. Similarly, Tipping et al. (1997) investigated a range of catchments of the River Humber, and found DOC to account for between 51 and 80% of export. In contrasting catchments in Mid-Wales and NE Scotland, Dawson et al. (2002) found DOC contributed 69 and 88% of fluvial export respectively. In a much broader assessment of fluxes, Hope et al. (1997b) concluded that for British rivers as a whole during 1993, 0.68 MtC of the fluvial carbon load was in dissolved form, representing 77% of fluvial loss.

A clear understanding of the dynamics of DOC and particularly POC flux in eroding systems is essential for efforts to model current upland carbon cycles, to predict changes in peatland carbon sinks in the future, and to manage soil carbon in peatland environments. One significant gap in current knowledge is that almost all of the previous work on POC/DOC proportions has been carried out in relatively intact peatlands. This is despite the fact that much of the UK upland peatland resources are significantly eroded (Tallis et al., 1997). As yet, sediment flux has not been studied explicitly for the comparison of POC and DOC flux in heavily eroded peatland systems. The most impacted catchment for which data exists is at Moor House in the north Pennines (Worrall et al., 2003), a system which is extensively eroded but shows evidence of widespread re-vegetation (Evans and Warburton, 2005). Worrall et al. (2003) calculated an overall carbon budget for this system and found POC to be the largest flux, accounting for ~68% of fluvial carbon flux. Re-vegetation of eroded north Pennine peatlands has led to much reduced erosion rates compared to the severely degraded peatlands of the southern Pennines (Evans et al., 2006), described as the most eroded in Britain (Rothwell et al., 2005). These “badland” landscapes (Tallis, 1997) represent the extreme end of a spectrum which runs to the relatively uneroded, DOC dominated systems studied by Hope et al. (1997a). The onset of peatland gully erosion in the southern Pennines correlates closely with climatic fluctuations in the Early Medieval Warm Period (Tallis, 1995, 1997). Predicted future climate changes, including warmer and drier summers,

**Fluvial organic
carbon flux from an
eroding peatland**

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

have the potential to exacerbate existing peat erosion and initiate further instability in these environments. Therefore, research into sediment and in particular POC fluxes are essential in these fragile upland systems.

This study aims to quantify and compare the relative roles of DOC and POC in the fluvial export of carbon from an actively eroding, peat dominated catchment in the southern Pennines, based on intensive monitoring data and modelling annual cycles. Sediment removal in peatlands has been investigated in the past (e.g. Labadz et al., 1991), and the importance of stormflow in sediment yields highlighted in upland peatland catchments (Evans et al., 2005). Due to the low density of peat sediments (Labadz et al., 1991), it is likely that carbon contents will vary with discharge as a function of stream power. This is due to the channel entraining varied portions of minerogenic sediments under different discharge conditions. Such variability of sediment in terms of quantity and quality should be considered when modelling annual carbon fluxes. With this in mind, the first part of this paper investigates the nature of carbon export through an intensive field campaign during and between storm events. Using empirical observations from this high temporal resolution data, annual flux estimates of both POC and DOC are modelled to outline the significance of each form of carbon export in heavily eroding peatland systems.

2 Methodology

2.1 Study site

The field site used in this study is Upper North Grain (UNG), a small headwater catchment of the River Ashop (see Figs. 1 and 2). This is part of the National Trust High Peak Estate is situated in the Peak District, southern Pennines, UK. Located at altitudes between 490 and 541 m OD and receiving approximately 1200 mm rainfall each year, the catchment is dominated by blanket bog. The catchment is relatively small, draining an area of 0.38 km², with rough grazing by sheep as the dominant land-use

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

(Rothwell et al., 2005). The catchment is heavily eroded with Bower Type I peat gullies (Bower, 1961), which in the upper reaches occur solely in a peat stratigraphy that often reach several metres in depth. The lower reaches of the gullies cut into the underlying bedrock, which is dominated by sandstones of the Millstone Grit Series (Wolverson-Cope, 1976). The sampling site for this study is located in these lower reaches of the catchment where the river channel flows on bedrock surfaces rather than within the deep peat stratigraphy.

2.2 Field sampling: short-term temporal variability

To assess short-term temporal variability of organic carbon fluxes, a period of intense field monitoring was undertaken. Over a two week period, stream water samples were extracted from Upper North Grain on an hourly basis using a Sigma 900 automatic water sampler. This monitoring took place in late March/early April 2005 during a period of storm events. Following each 24 h period, stream water samples were returned to the laboratory and processed using the methods outlined below. Laboratory work was undertaken within 72 h of extraction. The data set therefore consisted of over 300 direct measurements of DOC, pH, conductivity and suspended sediments. During this period, stage was recorded using an Intelysis pressure transducer and Sentry II data logger. A stage-discharge relationship (see Daniels, 2006) was used to determine discharge over the study period.

2.3 Field sampling: annual flux calculation

Water samples were extracted using a range of methods throughout 2004–2005. Sampling periods were distributed throughout the year and occurred at a wide variety of discharges. Samples included routine spot samples on a weekly basis, low flow sampling and storm discharge samples, each of which is summarised in Table 1. All samples were returned to the laboratory, stored in a dark cold room at 4°C, processed and analysed within 72 h of extraction from the catchment.

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Along with water samples, monitoring of stream chemistry (pH) and discharge was undertaken, providing a quasi-continuous field dataset. Monitoring encompassed the entire year (2004), facilitated again by Intelysis probes and data loggers.

A range of sediment samples from the catchment were characterised in terms of carbon content. This was undertaken to allow identification of in-catchment sources of sediment carbon, which could be then be used to estimate organic carbon flux from the peatland carbon store. This source characterisation entailed analysis of a range of potential source sediments taken from a wide area in the catchment. Potential source sediments were generalised as sandstones and mudstones of the Millstone Grit Series, the periglacial head deposits of reworked sandstones and mudstones and the peat itself. Five exposures of the main sediment types were selected with broad spatial coverage in the catchment, while peat samples were extracted from eroding gully walls and through peat coring. The method for peat core collection is summarised by Rothwell et al. (2005). All catchment sediment samples were analysed using the methods described below.

2.4 Laboratory methods

Stream water samples were vacuum filtered through pre-weighed Whatman GF/C glass microfibre filter paper circles to separate the suspended sediment fraction over 1.2 μm . Water volume of the filtrate was also measured. The sediment retained on the filter paper was dried for 24 h at 105°C to eliminate hygroscopic water and ensure accurate sediment weight. The filter papers were then re-weighed to determine suspended sediment concentration (SSC) as a function of water volume. The separated water and sediments were then analysed as described below.

2.4.1 Sediment analysis

Sediment samples of over 50 mg were milled using a silicon carbide grinder in a 240 V Glen Crest Ball mill. This homogenised the sediment and filter paper which allowed

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

repeated analysis of samples to determine the reproducibility of analytical techniques. Filter papers with less than 50 mg of sediment were left intact as the expected carbon content of this amount of sediment is within the range of measurement of laboratory instruments (R. Pawson, unpublished data). All samples were analysed for total carbon and total inorganic carbon using an SSM 5000A of the Shimadzu TOC-V Series Analyser. POC content was determined by total carbon minus total inorganic carbon. This allowed the calculation of POC concentration and % POC of SSC.

2.4.2 Water analysis

After stream water samples had been filtered through the $1.2\text{ }\mu\text{m}$ filter paper, each water sample was then filtered again using $0.45\text{ }\mu\text{m}$ Whatman cellulose nitrate membrane. Sub-samples of the filtrate were analysed for TOC (Total Organic Carbon) using the Shimadzu TOC-V Series Analyser. The $0.45\text{ }\mu\text{m}$ filtration size was used as this pore size is the common definition for DOC including colloidal carbon (Koelmans and Prevo, 2003) and has been routinely used in numerous studies for DOC determination (e.g. Scott et al., 1998; Chow et al., 2005 and Fujii et al., 1998). Stream water samples were also analysed for pH and conductivity.

3 Results: temporal variability of organic carbon flux

Figure 3 shows the results from the two week intensive study period. The discharge record shows relatively consistent, low values during the first nine days except for two main events where discharge rapidly increases over $0.01\text{ m}^3\text{ s}^{-1}$ and then returns to low flow. This nine day spell is then followed by more variable discharges with greater ranges of flow. As in the first nine days of monitoring, flows in the later part of monitoring are flashy and after a rapid peak in discharge, baseflow conditions are soon resumed.

DOC concentrations in the sample period vary by $\sim 20\text{ mg l}^{-1}$. Higher peaks in con-

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

centration of up to $\sim 25 \text{ mg l}^{-1}$ coincide with discharge peaks. Following these peaks, DOC concentrations gradually decline to $\sim 5 \text{ mg l}^{-1}$. This trend of rapid peaks and slow decreases of concentration is most pronounced in the first nine day period of relatively lower discharges. In the later period of more variable and increased discharge, DOC concentrations remain relatively higher, with lowest concentrations of $\sim 10 \text{ mg l}^{-1}$.

POC concentrations over the monitoring period are much more variable, with the greater values concentrated in the period after nine days. The preceding period shows very little change in POC concentration, with low values of $1\text{--}2 \text{ mg l}^{-1}$. In the later period, concentration peaks of up to $\sim 250 \text{ mg l}^{-1}$ are recorded. These POC peaks are more short-lived than those of discharge. For example, the samples one hour before and one hour after the maximum peak of 250 mg l^{-1} have values of 4 and 50 mg l^{-1} respectively, while concentrations of 4 mg l^{-1} are returned within 5 h of this peak.

DOC flux over the monitoring period was 128 kg; POC flux was 145 kg. Both fluxes were calculated using Eq. (1):

$$\text{TotalLoad} = K \sum_{i=1}^n (C_i Q_m) \quad (1)$$

where; K is a conversion factor to take into account the period of study, C_i is the concentration for each sample point, Q_m is the volumetric discharge for the time unit of each sample concentration and n is the number of samples. This equation is similar to that used by Walling and Webb (1981) except that volumetric discharge is used rather than mean discharge.

These figures give a total carbon flux for the two week monitoring period of 276 kg. Of this value, POC represents $\sim 54\%$ of carbon flux. Cumulative flux data show that for DOC, 95% of total flux (or 121 kg) was exported over $\sim 62\%$ of time. For POC the 95% flux value of 141 kg was exported in $\sim 8\%$ of time during the study period – or in just over 1 day.

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

4 Modelling annual carbon flux

4.1 DOC

Model inputs

DOC concentrations for the annual study were modelled using a pH-DOC relationship for stream water samples collected during the study period. The rationale for this model is that pH in these upland catchments is significantly controlled by the inputs of humic and fulvic acids from the peat profile (Daniels, 2006). These humic acids are the main contributor to DOC concentrations in peat systems (Tipping, 2003; Chow et al., 2005), resulting in high DOC and low pH levels in peatland hydrology (Worrall et al., 2003). Using the pH-DOC relation for stream water samples and pH logged at 15 min intervals for the study period, a quasi-continuous record of DOC concentrations was produced. Flux calculations were achieved using an equation similar to Method 3 from Walling and Webb (1985), where the amount of carbon exported for each time unit (e.g. 15 min interval) is calculated taking the measured concentration and mean discharge over each sample period with the assumption that this was consistent until the next sample. The carbon exported for each sample period was then summed to give the total carbon flux for the entire study period.

For annual flux, it is necessary to correct the final figure of DOC export for the input of C to the catchment via rainfall. Analysis of rainfall has not been undertaken for this study, so values reported by Worrall et al. (2003) are used to estimate the peat sourced DOC flux.

Model outputs

There is a strong relationship between stream water DOC concentrations and pH ($r^2=0.79$, $n=249$, see Fig. 4). As DOC concentrations increase, pH values decrease.

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

DOC can therefore be calculated given the equation below:

$$\text{DOC} = 102.61e^{(\text{pH}+0.3994)} \tag{2}$$

Using the empirical relationship between DOC and pH, modelled DOC flux from UNG is $21.7 \text{ gC m}^{-2} \text{ a}^{-1}$, equivalent to 9.10 tC a^{-1} . The standard error of the regression line was used to calculate the error for the annual dissolved DOC flux after histogram analysis of the data. DOC flux by modelling yields an annual DOC flux of $22.9 \pm 6.70 \text{ gC m}^{-2} \text{ a}^{-1}$. This estimate of DOC flux is a total flux (i.e. peat sourced and atmospherically sourced DOC). Using data presented by Worrall et al. (2003), peat sourced DOC flux at UNG is $19.9 \pm 5.77 \text{ gC m}^{-2} \text{ a}^{-1}$ or an absolute flux of 7.55 tC using Eq. (1).

4.2 POC

Model inputs

POC flux was modelled for the annual period using a sediment rating curve approach and the analysis of POC concentrations in the suite of sediment samples collected from the catchment. Two rating curves relating to flows above and below $0.10 \text{ m}^3 \text{ s}^{-1}$ and $\geq 0.10 \text{ m}^3 \text{ s}^{-1}$ were derived from 254 storm water samples representing 13 storm events between March 2003 and December 2004. Previous work in peatland streams has demonstrated that there is usually positive hysteresis in the suspended sediment-discharge rating relation (c.f. Evans et al., 2006). Therefore, a 45 min lag was used in the construction of the rating curves, i.e. SSC was related to Q_{t+45} . Back transformation errors for the sediment yield was corrected using the smearing estimator, since this technique is the most appropriate correction for sediment rating curves in peatland streams (Armstrong et al., 2006) The total sediment yield for UNG is $257.19 \text{ g cm}^2 \text{ a}^{-1}$ (or 97.73 t).

To calculate POC proportions, a range of catchment sediment samples were analysed for organic carbon contents. These samples included suspended sediments from

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

a range of baseflow conditions, storm samples and rising stage samples. The need for a broad range of suspended sediment samples is due to the control of discharge on sediment quality, forced by the effect of discharge on sediment dynamics. In total 47 suspended sediment samples from a range of flow conditions were analysed for POC.

5 Potential sediment source samples were also analysed ($n=28$) for carbon contents to allow correction of the suspended sediment POC data for peat sourced carbon. Using this data for POC and SSC at a range of discharges, a calibration was developed for the quality of sediment for a given discharge, with lower % POC at higher discharges. This calibration could allow for the variability of POC content with hydrological conditions and was applied to the modelled annual suspended sediment flux data for the entire annual period, thus providing a modelled POC flux.

10 For the two week intensive study, SSC concentrations were obtained for every hourly sample. This data could then be calibrated to POC using the SSC/POC relationship obtained for the annual flux. These concentrations were then converted to total export of POC using Eq. (1), yielding POC export for the two week intensive monitoring period.

Model outputs

The mean POC proportion for sediment loads was calculated as $47.2 \pm 4.10\%$ ($n=47$, 95% confidence). This is similar to POC proportions reported by Worrall et al. (2003) after Francis (1987), where the majority of upland suspended sediments are organic-rich, and that carbon makes up $\sim 50\%$ of this load. This $\sim 50\%$ load is confirmed by measurement of OC contents of a range of peat samples at UNG, in which carbon contents where $50.1 \pm 1.70\%$ (95% confidence). Characterisation of other sediment sources measured very low total carbon (TC) concentrations similar to the conclusions made by Spears and Amin (1981). Total carbon contents of $2.30 \pm 1.50\%$ for shale, $0.17 \pm 0.07\%$ for sandstone and $1.09 \pm 0.73\%$ for head deposits were recorded in this study. Of the source sediments, organic carbon measurement was below the range of measurement of the analytical methods employed, suggesting that there was no need to correct carbon contents of suspended sediment samples for non-peat sourced

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

organic carbon.

The short-term temporal variability data revealed that POC content varied significantly with discharge in terms of % POC of SSC and absolute carbon flux. Discharge and % POC in suspended sediments correlated in a non-linear continuous trend ($r^2=0.68$, $n=47$) (see Fig. 5). The curve of this trend was used to derive a modelled annual POC flux for UNG using the sediment-rating curve data. This model produced a total POC flux of 33.24 tC, equivalent to $87.5 \text{ gC m}^{-2} \text{ a}^{-1}$.

Based on the modelled DOC and POC flux data the total annual flux for peat sourced carbon from UNG is $107 \text{ gC m}^{-2} \text{ a}^{-1}$. This amounts to an actual flux of 40.8 tC, of which POC accounts for ~82%.

5 Discussion

5.1 Fluxes of organic carbon

The flux of both DOC and POC can be considered on both the short and annual scale. Estimation of carbon flux over the two week intensive monitoring period resulted in a total loss of ~276 kg. Of this, POC accounted for ~148 kg, equivalent to ~54%. This highlights the relative importance of POC in fluvial export, especially when considering the very low POC loads in the first nine days of the monitoring campaign.

The annual data provides a more striking insight of the relative roles of fluvial carbon export in eroding peatland catchments. The peat sourced carbon flux is 40.8 tC a^{-1} . This value has been derived using an empirical relationship between DOC and pH and the discharge-sediment quality measurements. Therefore, for the total carbon export value, POC accounts for ~82% of fluvial export in the catchment. This clearly highlights the significance of POC in upland eroding peatland systems such as UNG, especially when this value is compared to those previously reported in the literature. Normalising the flux to unit area allows comparison with previous work. In the case of the North Pennines, POC flux is reported as $19.9 \text{ gC m}^{-2} \text{ a}^{-1}$ (Worrall

HESSD

4, 719–745, 2007

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

et al., 2003). Other relatively high estimates of annual POC fluxes reported by the authors include; $34 \text{ gC m}^{-2} \text{ a}^{-1}$ (Francis, 1987), $38.82 \text{ gC m}^{-2} \text{ a}^{-1}$ (Labadz et al., 1991) and $31.3 \text{ gC m}^{-2} \text{ a}^{-1}$ (Hutchinson, 1995). In comparison, the estimate of POC flux from UNG is $87.5 \text{ gC m}^{-2} \text{ a}^{-1}$. The implication is that in severely eroding catchments rates of POC export may be much higher than has previously been recognised.

The DOC-pH relationship used to model DOC flux (Fig. 4) exhibits an r^2 value of 0.79. The scatter in the data can be explained by the variability of DOC concentrations with lower pH values during storm events. This scatter relates to the effects of strong mineral acid release from the peat during storm flow and the impact that this has on pH levels (Novák et al., 2005; Daniels, 2006). However, the regression model performs well in estimating DOC concentrations, with an error of 29%. Total DOC flux from the UNG catchment is higher than values previously cited in the literature. A corrected total flux of DOC is $19.9 \pm 5.77 \text{ gC m}^{-2} \text{ a}^{-1}$. Reported values from other headwater peatlands include; $15 \text{ gC m}^{-2} \text{ a}^{-1}$ (Scott et al., 1998), $115.0 \text{ kg ha}^{-1} \text{ a}^{-1}$ ($11.5 \text{ gC m}^{-2} \text{ a}^{-1}$, Hope et al., 1997a) and $9.4 \text{ gC m}^{-2} \text{ a}^{-1}$ (Worrall et al., 2003). The likely explanation for these high values is the eroded nature of the catchment. Extensive gully networks are likely to cause a depressed water table over a wider area of the catchment by increasing drainage (Tallis, 1973; Wallage et al., 2006). This expands the aerobic zone and thus raises DOC production (Worrall and Burt, 2005) and consequently leads to a higher annual flux of DOC per unit area. This suggests that the importance of enhanced carbon flux from eroding catchments in upland carbon cycles may extend beyond particulate export as DOC fluxes may also be significantly higher under such conditions.

Although the significance of POC in the carbon flux from eroding peat catchments is clear, the question of how this source interacts with atmospheric carbon cycles is less well understood. Evans et al. (2006) estimate oxidation from peat surfaces as residual wastage and predict that 30–40% of bare peat loss can be attributed to oxidation. Similarly Jacinteh et al. (2002) show that 29–46% of soil organic carbon eroded from fields in Ohio is mineralised within 100 days. Current research has shown that in controlled experimental conditions up to 25% of mass can be lost from peat samples on

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

an annual cycle and that this figure can reach 40% on a monthly scale (Pawson et al., 2006). If these figures are accurate and we consider the levels of POC flux presented in this paper, it appears that there is indeed a significant degree of atmospherically active carbon flux from eroding catchments. Work assessing such fates of POC is ongoing.

5.2 Temporal variability of carbon flux: implications for sampling

The results from the intensive two week period clearly demonstrate the episodic nature of POC export. For the majority of the period, POC concentrations are considerably lower than during the main period of export (Fig. 3). Such rapid, episodic, discharge related flux of POC is expected. Previous work investigating sediment dynamics in peatland systems (e.g. Labadz et al., 1991; Holden and Burt, 2002) has revealed positive hysteresis in discharge-sediment relations, attributed to sediment supply from peat surfaces (Evans et al., 2005). It therefore follows that POC concentrations, strongly affected by erosional inputs in these degrading systems, will exhibit similar characteristics. POC as a proportion of total sediment flux also varied with discharge (Fig. 5). This variability shows a trend of decreasing % POC as discharges and SSC increases. Similar sediment quality-discharge relationships have been attributed to increased mineral entrainment (Bradley and Lewin, 1982; Dawson and Macklin, 1998; Rothwell et al., 2007). At lower discharges low density peat sediments make up a higher proportion of sediment loads and thus higher POC concentrations are recorded. Even though % POC is higher in these lower discharge periods, actual POC concentrations are still significantly lower than during higher discharge events, (e.g. $\sim 250 \text{ mg l}^{-1}$ peak, compared to $1\text{--}2 \text{ mg l}^{-1}$ at low flow). The idea of variable organic component is supported by loss on ignition measurements of suspended sediments at a range of discharges (R. Pawson, unpublished data). These results suggest that POC flux analysis requires carefully constructed sampling regimes at a variety of discharge conditions. As sediment supply is usually the controlling factor for sediment flux (Evans et al., 2005), then it is also essential that POC flux work investigates a wide spectra of antecedent, prevailing conditions. For example, high discharge conditions may not necessarily result in greater

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	

POC flux if antecedent conditions are not suitable for sediment preparation. The need for careful field sampling is reinforced in the present study. Firstly, POC concentrations decrease rapidly following peaks, returning to a “pre-peak” value within a few hours. The majority of POC flux (95%) therefore occurs in a small amount of time. As such, infrequent periodic sampling will miss peaks of POC export. Conversely, if sampling occurs during a peak then POC export could be significantly over estimated as peak concentrations are extrapolated beyond their true timescale. Furthermore, the POC-discharge relationship shows considerable hysteresis. The largest peak of POC over the period (Fig. 3) follows the first significant discharge peak ($Q=0.09$) after nine days of low flow. Following this, discharge is much more variable. A similar peak ($Q=0.07$) occurs 27 h after the first peak. However, this second event results in a much lower peak POC concentration. The reduction most likely represents a sediment exhaustion effect due to the limited pre-storm period for sediment preparation by weathering. In general the storm POC concentrations are significantly higher than those reported elsewhere (e.g. Dawson et al., 2002). Observation of sediment supply related hysteresis in the POC-discharge relation suggests that suitable antecedent conditions are likely to be required to create high peaks in POC export, and that monitoring regimes need to consider these ideas carefully.

DOC concentrations also showed variability over the study period, but with a much lower range of values. Whereas POC ranged from 0–250 mg l^{-1} , DOC has a range of 6.20–22.4 mg l^{-1} . These concentrations appear lower than reported values mentioned above, but it is likely that this characteristic is seasonal, as it has been shown that DOC concentrations are at their lowest in winter and spring months in peatland environments (Scott et al., 1998). DOC and discharge also appear to peak concurrently, but the level of discharge increase appears to have less effect on the concentration than with POC. For example, three days a small peak in discharge ($Q=0.01$) causes a rapid rise in DOC from ~10–22 mg l^{-1} , while a similar peak of DOC also occurs at the largest discharge peak ($Q=0.09$). As such, it appears that the level of discharge increases do not control the increase in DOC concentration (i.e. similar peaks in DOC

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

are forced by very different storm events). This is evidenced by the poor relationship between DOC and discharge. The Q-DOC relationship exhibits a low r^2 value (0.15), caused by the scatter of the DOC concentrations with variable discharges. This is due to similar peaks of DOC occurring concurrently with a range of discharge peaks, as noted. In comparison, POC correlates much more strongly ($r^2=0.45$) with these higher discharges in spite of the likely presence of hysteresis loops.

Following DOC peaks, concentrations decline slowly unless discharge remains high and variable. In these conditions, DOC varies less and remains at higher concentrations. Similar observations of falling DOC concentrations following discharge peaks have also been noted by Worrall et al. (2002) who describe DOC flux as a function of a three end-member system, with inter-event water dominated by low DOC while storm flow is dominated by a mixture of DOC rich and poor waters, sourced from old water within the peat profile and rainwater respectively. The author's refer to the rapid rises in DOC as event water (rainfall, runoff and through flow) exporting an existing supply of DOC rich water. The authors hypothesise that the time between events and the antecedent conditions will control this supply of dissolved carbon. In contrast to our study, Worrall et al. (2002) sample a period in autumn which is referred to as the re-wetting period of the peatland after the summer. As such, they propose that this flushing of DOC during storm events may be restricted to that time of year as the water table rises through the acrotelm where the DOC is sourced. However, it appears that this study supports the idea of a flushing of an existing carbon supply also during a spring period and that level of increased discharge is not a direct control of the DOC concentration of this flush water.

Due to the rapid increase in DOC concentration, the temporal variability of DOC does appear to vary with discharge on an event scale basis. The slow decline of DOC after such an event and the much smaller overall range of concentrations does mean, however, that the sampling implications of temporal variability in DOC flux are less significant than those identified for POC data. This is highlighted by the results of the flux analysis. As highlighted above, 95% of POC export occurs in just 8% or 27 h of the

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

study period. In comparison, 95% of DOC export occurs over much longer periods of ~62% – or over 208 h (>8 days).

6 Conclusions

- In contrast to most previous work on carbon export from peatland catchments, this study has revealed that POC is the dominant component of fluvial organic carbon flux from the Upper North Grain catchment. UNG lies at one end of a spectrum from eroding peatlands through eroded and re-vegetated systems to the intact peatlands where most previous work on the balance of POC and DOC in runoff has been conducted. The results of this study emphasise the importance of adequately considering the POC flux as a component of the carbon budget in systems where erosion is significant.
- The temporal variability of POC flux demonstrated here means that it is not only important to consider POC flux as a significant part of the carbon budget but that in catchments where it is important higher resolution sampling than the standard weekly measurement are required to adequately characterise the flux.
- Potential increases in DOC flux associated with climate warming are well documented but the historic association of erosion with periods of climate change also suggests a risk of increasing POC flux.
- Given the significance of POC flux from eroding systems further research is urgently required to consider the fate of particulate carbon in the fluvial system and the proportion which might be expected to become climatically active.

Acknowledgements. We thank the University of Manchester, School of Environment and Development for the provision of a Graduate Teaching Fellowship (to R. R. Pawson) and Moors for the Future Partnership for the provision of a Small Project Grant for fieldwork and analytical expenses. The authors would also like to thank the National Trust for allowing fieldwork to be carried out at Upper North Grain.

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

References

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HESSD

4, 719–745, 2007

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

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Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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HESSD

4, 719–745, 2007

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Table 1. A record of the samples used for the pH DOC calibration in this study.

Sample type	Dates	Number of samples	Description
Routine spot samples of main UNG monitoring point	November 2005–January 2006	20 samples	Weekly to bi-weekly routine sampling
High discharge sampling of main UNG monitoring point	November 2005–January 2006	9 samples	Grab samples collected at points of storm discharge
Intensive Monitoring period (AWS)	28/03/2005–11/04/2005	Twice daily spot sampling (28)	Hourly sampling using automated water samplers (AWS)
Storm Sampling (AWS)	February 2004–February 2006	24 samples for 6 events, 48 for 1 events	High discharge, flow triggered sampling using AWS
Total Samples	249		

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Fluvial organic
carbon flux from an
eroding peatland**

R. R. Pawson et al.

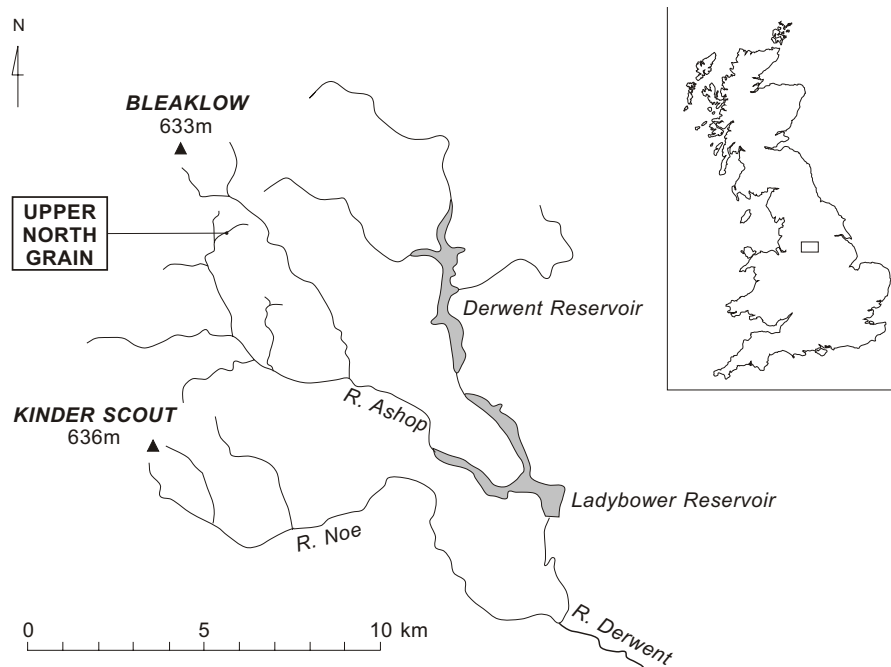


Fig. 1. Location of study site Upper North Grain (UNG) in the Southern Pennines.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

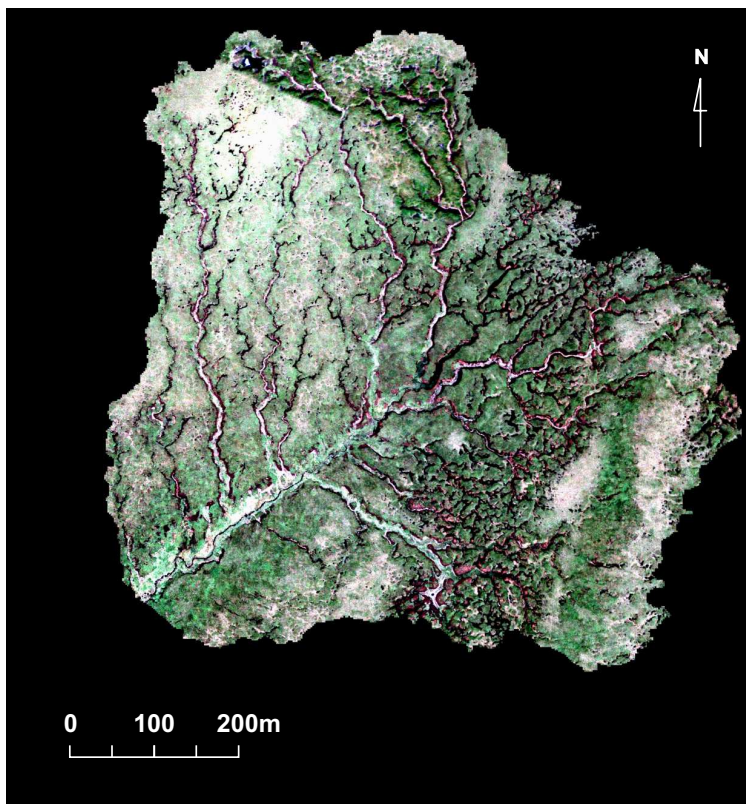


Fig. 2. Aerial photograph of UNG catchment displaying the blue, green and near infrared bands. The dendritic gully networks are clearly visible.

HESSD

4, 719–745, 2007

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

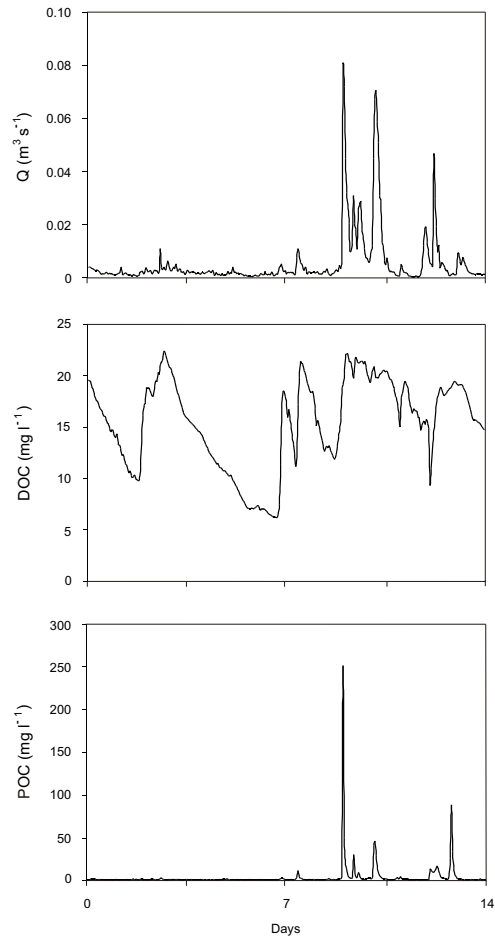


Fig. 3. Discharge, DOC and POC concentration data for the two week intensive study period. Note the changing y scale.

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

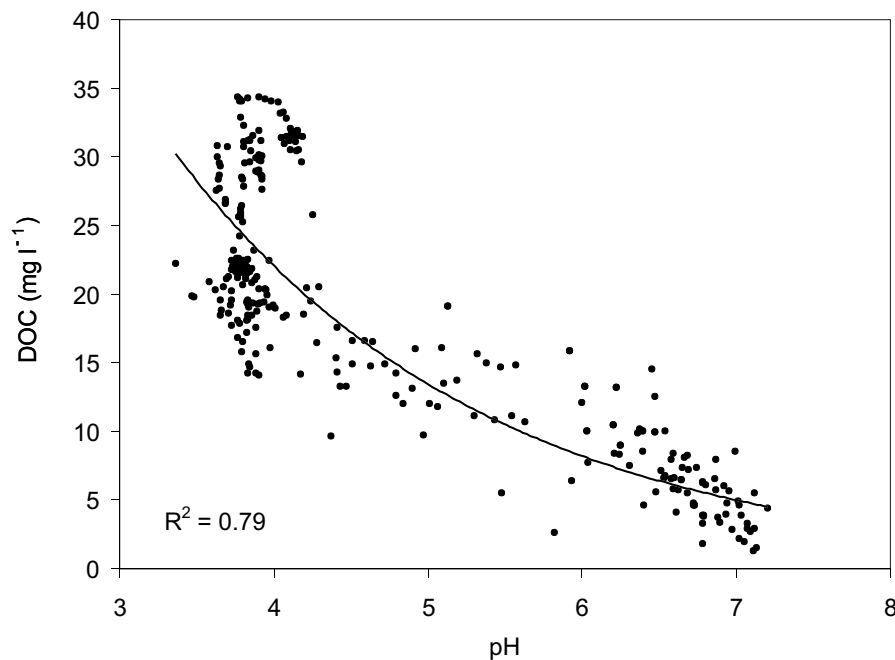


Fig. 4. Graph showing relationship of DOC and pH for all samples (n=249). Residuals are normally distributed and error calculated as 29% for this model.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Fluvial organic carbon flux from an eroding peatland

R. R. Pawson et al.

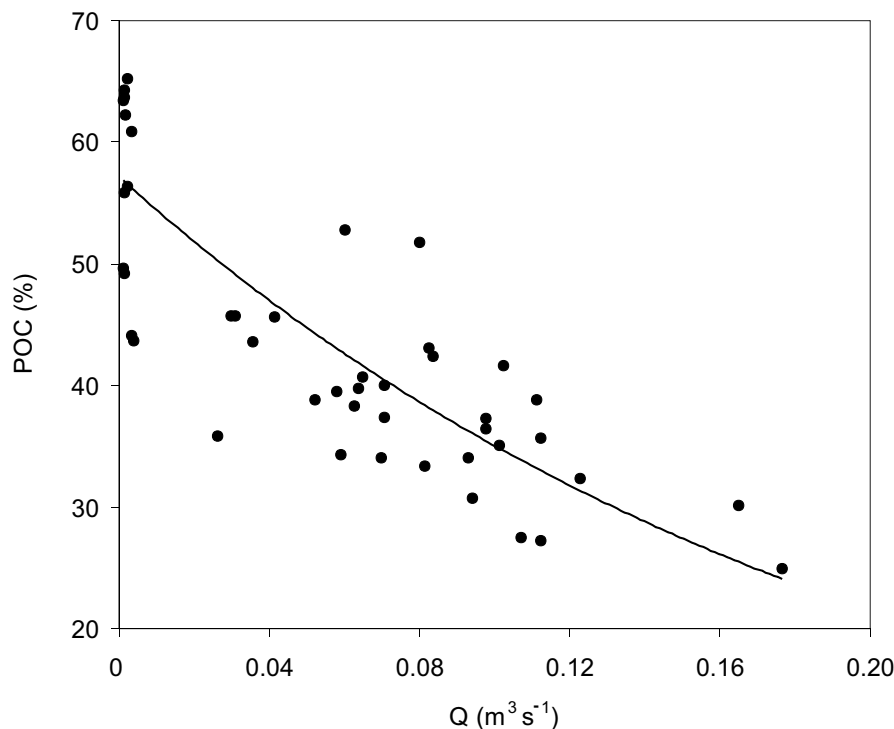


Fig. 5. Graph showing relationship between POC concentrations (%) in suspended sediments against discharge in study catchment ($r^2=.68$). The curve is added to show the trend of decreasing POC contents with increasing discharge. This is used for the calibration of SSC for POC concentrations. ($n=47$).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion